

# **Mixing by Tidal Interaction with Sloping Boundaries**

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## **LONG-TERM GOALS**

The long term goals of this project are to obtain an understanding of the mechanisms by which tidal energy is used to vertically mix the ocean against the action of gravity. Ultimately better parameterizations of the mixing caused by tides will result, allowing better prediction of coastal dynamics, biogeochemistry and sediment transport and the oceanic general circulation.

## **OBJECTIVES**

The process of mixing by tides interacting with topography involves several stages. First some fraction of the energy contained in the barotropic tide must be converted into baroclinic energy, through the generation of internal tides and turbulent boundary layers. Secondly, the energy in the internal tides must be transmitted into smaller vertical wavelengths, thereby increasing the vertical shear of the motion. When vertical shears are sufficiently strong, instability may result, leading to overturning and mixing. Finally, the mixed fluid is transported away from the mixing region modifying the ocean stratification. The net effect of the tides on the ocean stratification depends on the efficiency of all three processes.

Our objectives are to understand (a) the generation of internal tides by the interaction between barotropic tides and topography including finite-amplitude three-dimensional variations in topography, finite-amplitude barotropic tidal forcing, non-hydrostatic effects and the boundary layer processes; (b) the mixing generated by internal tides reflecting from a sloping boundary in the presence of both two- and three-dimensional variations in slope, and finite rotation; and (c) the mechanisms of lateral and isopycnal transport of mixed fluid away from the boundary induced by the secondary circulations generated through spatial variations in mixing. Earlier studies have ignored three-dimensional large amplitude variations in topography and non-hydrostatic effects (which are important for small-aspect ratio motion).

## **APPROACH**

We use high-resolution numerical simulations to explicitly resolve the turbulent mixing processes. For such simulations we require a numerical model which can (a) capture the non-hydrostatic physics of overturning and mixing processes (b) include arbitrary three-dimensional variations in topography. The Marshall et al (1997a,b) code (known as the MIT ocean model), which is non-hydrostatic, and includes topography through a finite-volume formulation, is such a model.

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We are carrying out three different groups of simulations: (a) We impose topography, barotropic tides and subinertial flows suggested by recent observations (*e.g.*, the region of the TWIST field program, Polzin *et al.*, 1998 and Monterey Canyon region, Petrucio *et al.*, 1998), and investigate the internal tide generated by the flow-topography interactions, comparing these results with earlier models which assume small-amplitude (*e.g.*, Bell, 1975) or two-dimensional finite-amplitude (Baines, 1982) topography. (b) We impose internal tide forcing and investigate the interaction with a two-dimensionally varying slope, focusing on the influence of finite rotation on the overturning and mixing, and the effect of slope variations in localizing mixing, comparing with earlier laboratory and numerical studies with uniform slope and no rotation (Ivey and Nokes, 1989; Slinn and Riley, 1996). (c) We impose internal tide forcing and investigate the interaction with three-dimensional topography variations, focusing on the localization of mixing, and the resultant secondary circulation and lateral transports of mixed fluid.

## WORK COMPLETED

In the past year we have focused on internal tide generation and reflection in the TWIST region, working closely with Kurt Polzin to compare results with observations. We have carried out the following series of simulations.

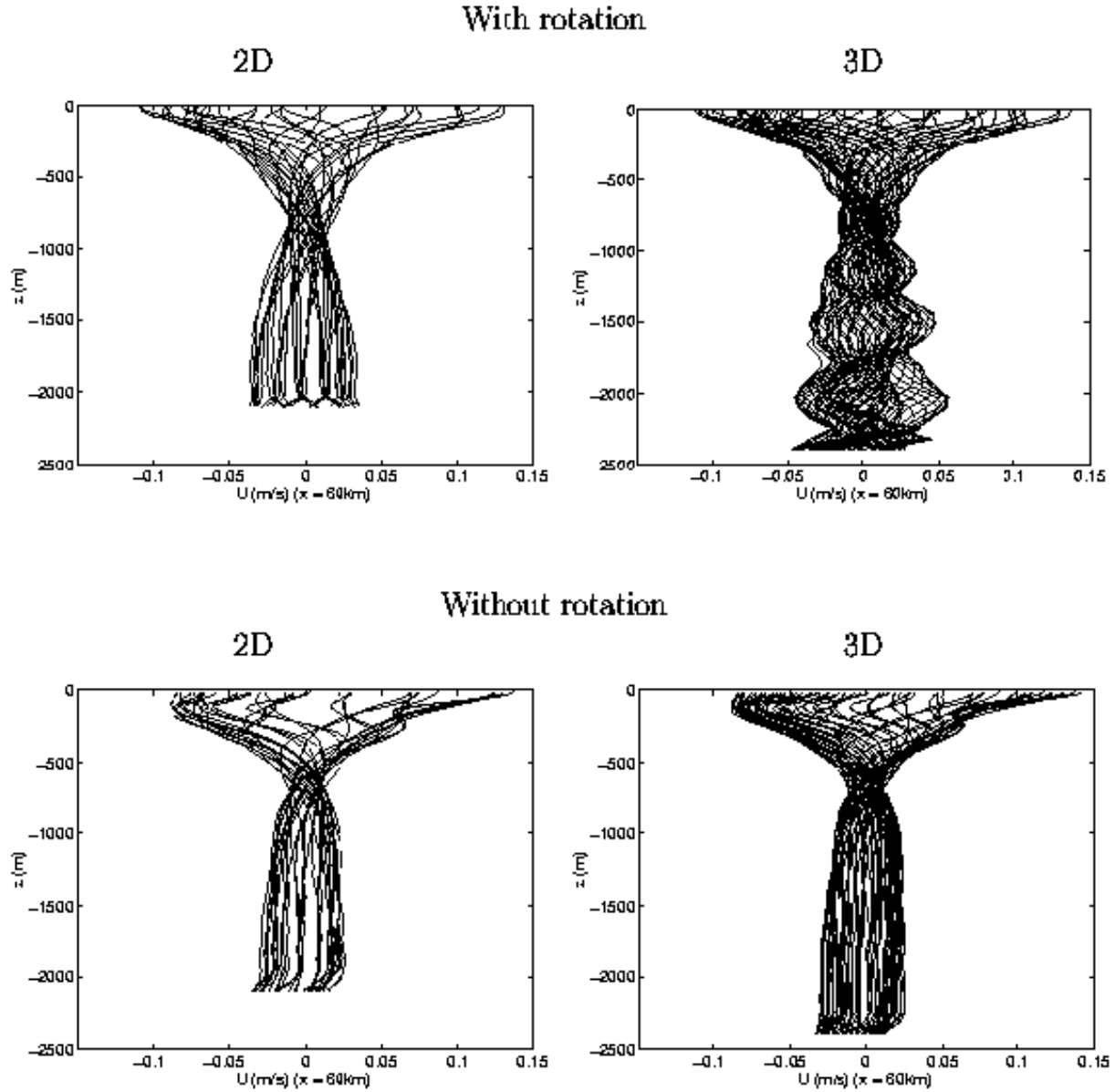
Data from the LIWI funded TWIST project (Kurt Polzin, PI) have been used to initialize the stratification and topography for a region of the East Coast. We force the model with either the cross-slope barotropic tidal signal (imposed at the off-shore open boundary) or with the along-slope barotropic tidal signal (imposed through a body forcing term). We investigate the baroclinic response generated by the interaction between the barotropic flow and the three-dimensional topography, typified by a continental slope with corrugations of about 3-km wavelength-orientated up and down the slope.

## RESULTS

### ***1. Small Vertical Scales Caused by Cross-Slope Tide Interaction With Corrugated Topography:***

With smooth continental slope topography, the response to cross-slope barotropic tide forcing is typified by an internal wave generated at the shelf break, which upon reflection from the bottom, tends to the lowest vertical mode. Shear is confined to mid-depths (the node of the mode), with no shear near the bottom topography (Figure 1).

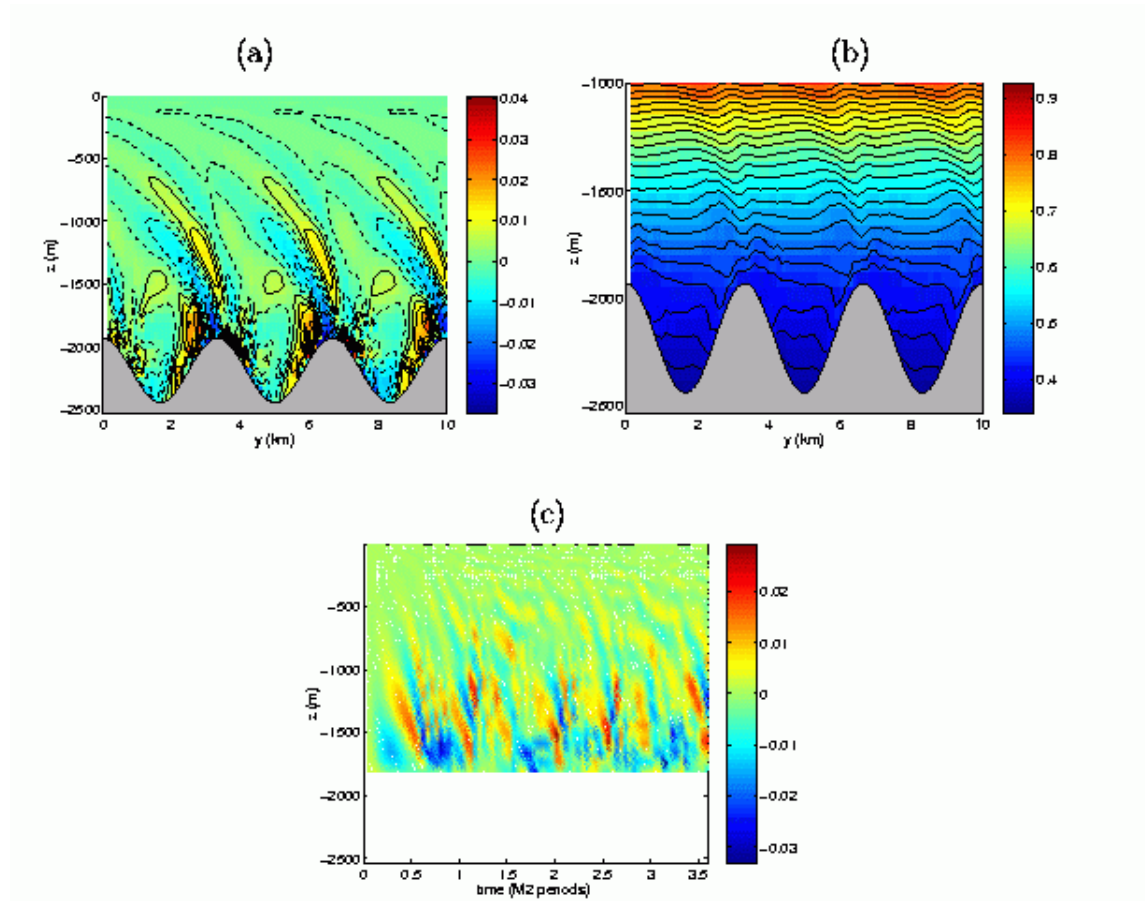
However, when sinusoidal corrugations of lengthscale 3.3 km running up and down the slope are included in the calculation, smaller scale structure appears, resulting in zones of shear all the way down to the bottom topography. This shear structure appears to result from the reflection of the internal wave generated at the shelfbreak from the corrugated topography, a hypothesis confirmed by more idealized calculations, where the continental slope is replaced by a cliff, and corrugations are placed on the flat bottom near where reflection of the shelf-break internal wave occurs. The shear structure appears modal in character, with nodes of limited temporal variability, separating regions of enhanced temporal variability, and possibly results from interference between the scattered wave components and the primary wave. The high mode structure is confined to the region above the corrugations, and does not propagate away from the topography. Most interestingly, this high mode structure is completely absent when rotation is neglected, suggesting that existing theories of internal wave scattering from corrugated slopes (*e.g.*, Thorpe 2001) are inadequate to explain this behavior,



**Figure 1: Cross-slope velocity profiles from the numerical simulations at a location above the continental slope. The lefthand column shows profiles from two-dimensional simulations, the righthand column shows profiles from three-dimensional simulations including corrugated topography. The top row shows results where planetary rotation is included, the bottom row shows results where planetary rotation is omitted. The two-dimensional calculations show a mode-1 internal tide, generated at the shelf break, without any shear near the bottom of the water column. The three-dimensional calculation without rotation is similar to the two-dimensional calculation. However, the three-dimensional calculation with rotation (top right) shows much higher mode structure, with bands of shear all the way to the bottom, generated by the interaction between the rotating internal tide and the corrugated topography.**

since they neglect rotation. Encouragingly, the observations also show high mode structure in the baroclinic velocity field above the slope. This reflection from corrugated topography could be an important mechanism for generating shears sufficient to lead to local mixing; indeed our simulations at large values of forcing lead to shear instability above the corrugations when the Richardson number is less than  $\frac{1}{4}$  (again completely absent if rotation is neglected).

**2. Small Vertical Scales and Mixing Caused By Along-Slope Barotropic Tide Interaction With Corrugated Topography:** For strong forcing and relatively large amplitude corrugations, we have found an interesting flow regime characterized by time dependent internal hydraulic jumps on the downstream side of the ridges (Figure 2a and b).



**Figure 2: Color contour plots showing the response of the flow to barotropic tide flowing along the mean isobaths, over a corrugated slope. The top two panels show the instantaneous fields of (a) vertical velocity (m/s) and (b) temperature (relative to the bottom) (K) as a function of depth and alongslope distance, at a time 0.67 tidal periods after the start of the calculation. Downstream (*i.e.*, to the left) of the ridges, there are internal hydraulic jumps. The bottom panel shows a color contour plot of vertical velocity (m/s) as a function of time and depth at a location above a ridge on the continental slope. Twice every tidal period an upward propagating wave packet is released, as the internal hydraulic jump downstream of the ridge relaxes.**

As the barotropic flow relaxes and reverses direction, these jumps propagate upstream, and initiate an upward propagating wave-packet, typified by small vertical scales, and high-frequency oscillations. Two such wave-packets are generated during every tidal cycle, and provide a mechanism for forcing small-scale shears high in the water column above the corrugated topography (Figure 2c). The internal hydraulic jumps are associated with significant mixing downstream of the ridges. Hence along-slope barotropic forcing is a mechanism for generating mixing both in close to the bottom topography, and higher in the water column. Existing theories, which concentrate on small-amplitude corrugations and linear wave responses (Bell, 1975; Thorpe, 1996) are insufficient to describe this flow, although they provide useful guidance for smaller amplitude forcing and topographic variation scenarios.

For lower amplitude forcing, interesting behavior is observed where the slope changes from subcritical to supercritical. Internal waves generated over the corrugations in the subcritical region appear to propagate into the region of supercritical slope, where they reflect and lead to interference.

## **IMPACT/APPLICATIONS**

Our results are helping in the interpretation of observations of tidally forced flows on the continental slope observed by LIWI investigators and others. Our results are demonstrating mechanisms for exciting small vertical scale baroclinic response to barotropic flow over topography. These small vertical scales (and hence large shears) are essential if the tidal forcing is to generate mixing, as widely speculated in recent years. We anticipate our results will eventually allow better parameterizations of tidal mixing to be developed, allowing better prediction of coastal dynamics, biogeochemical processes and the oceanic general circulation (Munk and Wunsch, 1998).

## **TRANSITIONS**

We are actively communicating results with K. Polzin, E. Kunze, J. Nash, R. Street, and R-C Lien, to help interpret observations made during LIWI and compare with other numerical simulations of these phenomena.

## **RELATED PROJECTS**

This project examines processes closely related to observations included in LIWI (Polzin, Toole and Schmitt and Paduan, Rosenfeld, Kunze, and Gregg).

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